Jerzy Niagaj, Adam Jędrusiak

The Effect of Shielding Gas Composition and Orbital TIG Welding Parameters on the Dimensions and Quality of Austenitic Stainless Steel Pipe Girth Welds

Abstract: The article presents the results of orbital welding of AISI 304 (1.4301) austenitic stainless steel pipes using a closed welding head. The article-related tests revealed that an increase in a helium content in a shielding gas mixture increases a penetration depth with a little impact on a weld width. It was also found that an increase in welding current and a decrease in a welding rate can ensure full penetration, yet at the same time it can lead to the formation of imperfections in the form of an incompletely filled groove at 9h and 12h and/or an intermittent undercut at 3h. Welded joints of austenitic stainless steel pipes are characterised by the highest concentration of imperfections at 3h and 9h (incompletely filled grooves and intermittent undercuts) regardless of the type of a shielding gas used.

Keywords: orbital welding, AISI 304, austenitic steel, shielding gas, welding imperfections

Introduction

One of the TIG method application areas is the orbital welding of pipes using special equipment provided with appropriate control systems. Thin-walled pipes (usually of thicknesses not exceeding 2 mm) of relatively small diameters are usually welded without bevelling and without filler metals using closed heads (Fig. 1a). Pipes of greater diameters and wall thicknesses are joined using open heads (Fig. 1b).

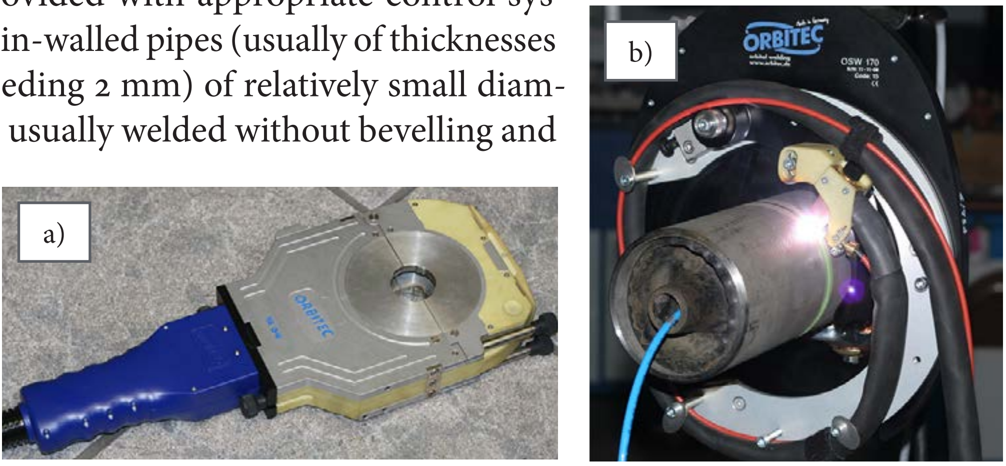

Fig. 1. Heads for orbital TIG welding: a) closed head; b) open head

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dr inż. Jerzy Niagaj (PhD (DSc) Eng.), Professor Extraordinary - Instytut Spawalnictwa, Welding Technologies Department, mgr inż Adam Jędrusiak (MSc Eng.)

Table 1. Chemical composition of 1.4301 (AISI 304) steel according to PN-EN 10088-2

Steel grade	Chemical composition, % by weight						
	C	Si	Mn	S	P	Cr	Ni
1.4301X5CrNi18-10	≤ 0.07	≤ 1.00	≤ 2.00	≤ 0.015	max. 0.045	17.00-19.50	8.00-10.50

To the greatest extent, the quality of girth welds is affected by orbital welding parameters, i.e. current and welding rate, requiring precise adjustment in relation to a welding position. However, orbital welding results also strongly depend on the composition of the shielding gas affecting the geometry of welds (run shape and penetration depth), surface condition (oxidation), protection effectiveness (gas atmosphere composition in the arc area), corrosion resistance (protection against air access, surface oxidation), metallurgy and mechanical properties of welds (oxidation, introducing nitrogen or the evaporation of alloying elements), arc stabilisation and initiation, and the natural environment (emission of fumes and gases) [1].

TIG welding of stainless austenitic steels involves the use of inert shielding gases and their mixtures. The most popular and commonly applied gas is technically pure argon. The use of helium and a mixture of helium and argon, or those of argon with a small amount of hydrogen or nitrogen is possible, yet in comparison with argon it is significantly less popular in industrial practice, mainly during highly efficient mechanised welding. During TIG welding, shielded gases are also tasked with ionisation and enabling the initiation of the welding arc, arc burning maintenance and the protection of a weld pool against the access of nitrogen and oxygen from air.

Below are presented test results concerning the effect of shielding gas composition and orbital TIG welding parameters (closed head) of pipes made of AISI 304 (1.4301) stainless austenitic steel (wall thickness of 3.5 mm) on the shape and dimension of welds in the individual areas of a welded joint as well as on the quality level of these joints against the requirements of PN-EN ISO 5817 [2].

Test Materials

Orbital welding tests involved the use of pipes made of AISI 304 (1.4301) austenitic stainless steel having an outside diameter of 42 mm and a wall thickness of 3.5 mm; the steel chemical composition according to PN-EN 10088-2 is presented in Table 1.

Shielding and Forming Gases

Orbital welding tests involved the use of argon, helium and their 50:50 mixture as shielding gases. The chemical compositions of shielding gases and that of the forming gas are presented in Table 2.

Table 2. Chemical composition of shielding gases and of forming gas, used during welding

Gas symbol	Gas type	Designation according to PN-EN ISO 14175	Component content, %	
			Ar	He
Ar	shielding	I1	100	
Ar/He		I3	50	50
He		I2		100
Ar	forming	I1	100	

The greatest popularity of argon as an inert shielding gas is due to its low price. Most materials, including high-alloy stainless steels, are welded using argon of 99.99% technical purity as a shielding gas. Argon ensures the easy initiation and stable burning of an arc. It is heavier than helium; therefore, during welding its consumption is lower. Argon is also known to protect a welding area better in all positions, except PD and PE.

In turn, helium is characterised by a high ionisation potential and approximately 8.5 times greater thermal conductivity (0.001513 W/cm·K) than argon (0.0001772 W/cm·K), which translates to a greater heat input to a workpiece and as a result, deeper penetration and/or a higher welding rate. These features are utilised while welding thick plates, materials of high thermal conductivity and during processes conducted at high welding rates. However, helium high ionisation energy (24.6 eV) impedes the initiation of a welding arc. The gas is lighter than air, which determines its application in overhead positions. Similarly, as in the case of argon-shielded welding, helium-shielded TIG welding of austenitic steels requires the use of helium of a purity amounting to 99.99%.

Mixing argon and helium enables taking advantage of the features of both gases, i.e. the possibility of obtaining greater penetration than with argon alone, stable arc burning and easier arc initiation with sufficient weld pool protection.

Orbital Welding Equipment and Parameters

Orbital welding tests were performed using a Tigtronic Orbital 3 controlled with a closed head manufactured by Orbitec and a Tetrix 351 welding current source produced by Ewm.

The orbital welding of thin-walled pipes using a closed head is usually carried out by making a single run butt weld. The process of welding starts with the initial outflow of shielding gas filling up the head chamber (usually argon). The head starts to rotate with a delay needed for the formation of a liquid metal pool. The rate of rotation is selected following the principle stating that a welding rate should amount to approximately 5 inches (130 mm) per minute. The head rotation exceeds 360° as the final sector overlaps the first one in order to obtain full penetration along the whole length of a weld. Once the head has performed the whole rotation an arc is gradually terminated. Welding current is adjusted in accordance with the following principle: 1 A per 0.001 inch (0.0253995 mm) of the wall thickness. This value is proper for the first sector as it is recommended in order to reduce current in each successive sector to prevent the root concavity caused by excessive heat input. Usually, pulsed current is used, with a pulse current to base current duration ratio being 1:1. Such a ratio makes it possible to control the weld pool in individual sectors. While welding high-alloy (inclusive of stainless austenitic steel) pipes, a shielding gas is blown into them in order to form the root of the weld and protect it against air access. Similarly, as with gas filling up the head chamber, forming gas starts flowing before the start of a welding process and follows the completion of welding until the joint cools down to reach a temperature preventing the formation of tarnish colours [3].

Independent of equipment, a programmer, being part of the orbital welding station, enables the division of the pipe circumference into sectors. In each sector it is possible to adjust other welding parameters. In the case of girth welding, when the pipe axis is perpendicular to the force of gravity, the division into sectors is necessary as welding is performed in two positions – pipe position for welding downwards (PJ) and pipe position for welding upwards (PH). Each of these positions requires slightly different parameters [4, 5]. The most important parameters defined for a given process are welding current, base current, welding current flow time, base current flow time, welding rate, head rotation delay time after welding start, current drop time after arc termination, welding time at specific parameters on a given pipe sector and overlap run making time; more conveniently these values can be determined using the head rotation angle [6].

The test joint was welded without filler metal, using the TIG method and a pulsed arc, with a pulse current to base current duration ratio being 1/1. The value of the base current amounted to 44 A. The electrode used was made of tungsten doped with thorium dioxide (WTh20). The distance between the electrode and the material was constant in each test and amounted to 2 mm. The shielding gas flow amounted to 12 l/min whereas the forming gas flow was 6 l/min. The head rotation direction was anticlockwise, i.e. from 9 hours backwards (Fig. 2). The gas outflow prior to the commencement of welding lasted 15 s, the formation of a weld pool – 9 s, the time of current drop until the termination of an arc lasted 15 s, and the outflow of gas following welding arc extinction was 15 seconds long.

Fig. 2. Orbital welding direction for horizontally positioned pipes (KL0)

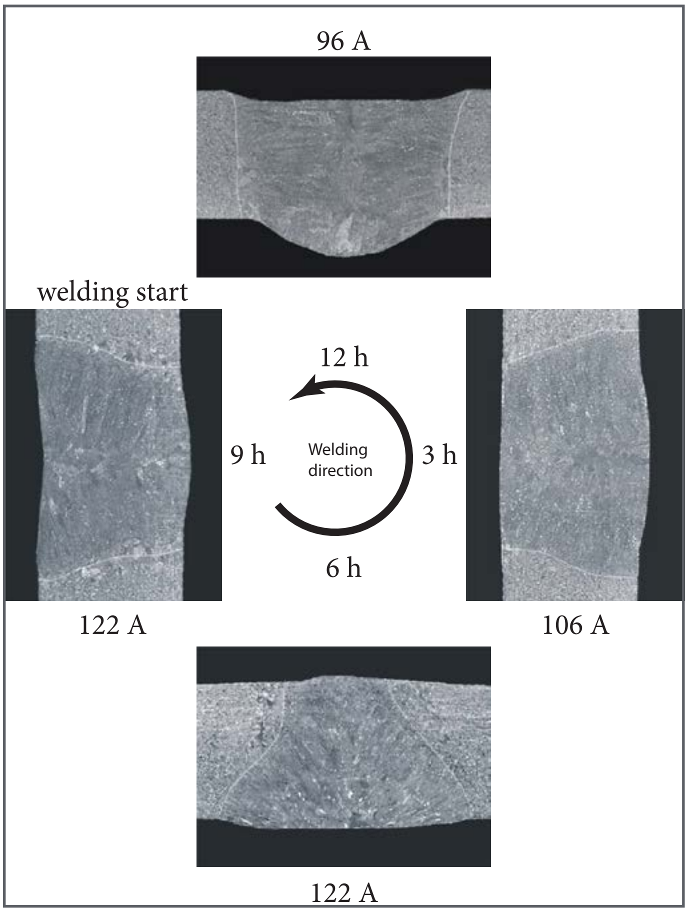


Fig. 3. Macrostructure of orbital He-shielded TIG welded joint

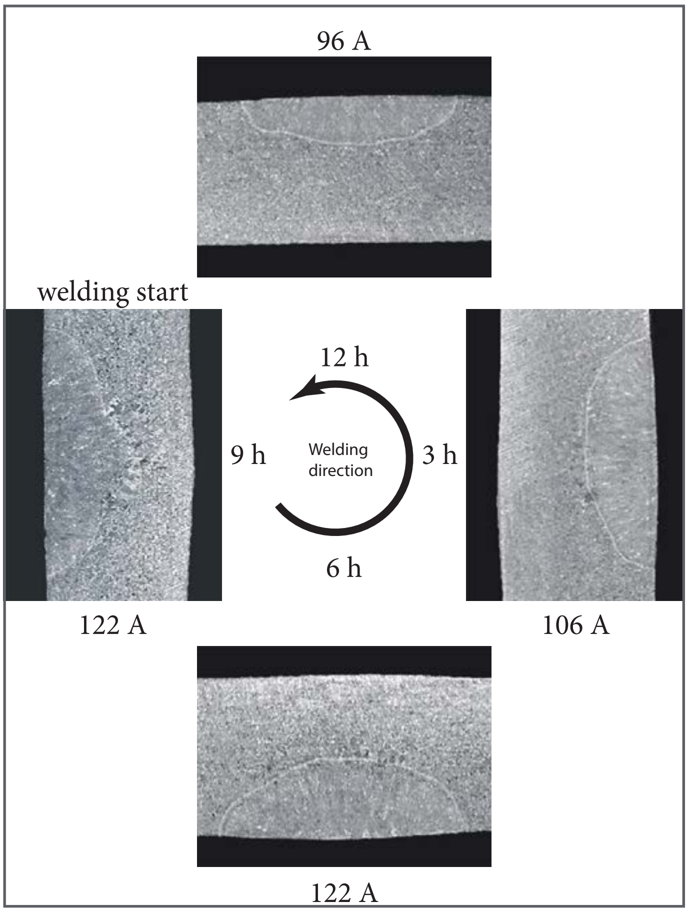


Fig. 4. Macrostructure of orbital Ar-shielded TIG welded joint

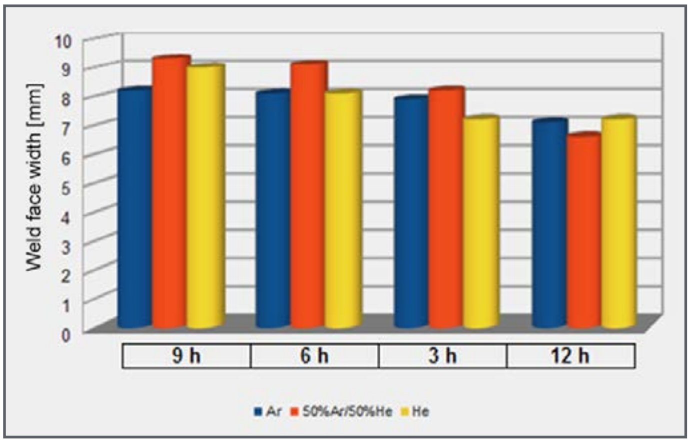


Fig. 5. Effect of a shielding gas used on the width of a weld

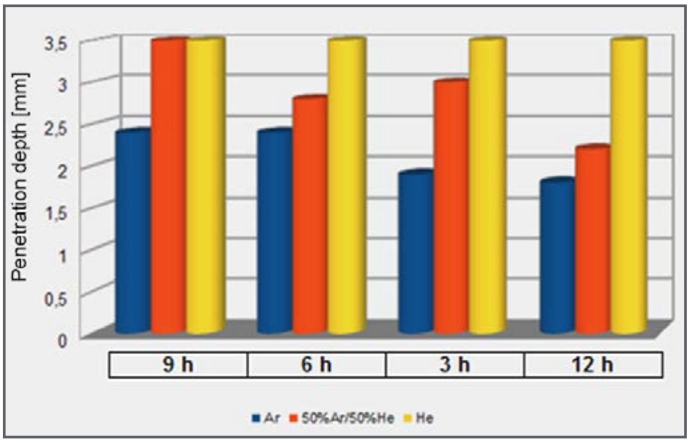


Fig. 6. Effect of a shielding gas used on penetration depth

Tests Results and Analysis

Effect of a shielding gas on the shape and dimensions of welds

The first stage of tests involved orbital welding with helium used as a shielding gas. The welding parameters were adjusted so that it was possible to obtain the full penetration of the parent metal around the whole pipe circumference. Next, the parameters were used for argon-shielded welding and for welding shielded by the mixture of argon and helium (50/50). Welding was conducted at a welding rate of $V_{sp}=100\pm2$ mm/min using pulsed current, where the base current was 44 A, the current of pulse amounted to 122 A in quarters 1 and 2, 106 A in quarter 3, and 96 A in quarter 4. Helium-shielded welding led to the obtainment of full pipe wall penetration on one side, yet on the other side it was possible to observe weld shape imperfections, which in some joint areas were significant (Fig. 3).

Argon-shielded orbital welding involved the use of the same parameters as those applied during helium-shielded welding. The macrostructure of the joint made with argon used as a shielding gas is presented in Figure 4. In the welding conditions adopted, the use of argon

Table 1. TIG welding parameters, weld dimensions and the quality level according to PN-EN ISO 5817 of the test joints made with Ar used as a shielding gas

Argon *

Specimen no.	Current [A]				Welding rate Vsp [mm/min]			
	9 h	6 h	3 h	12 h	9 h	6 h	3 h	12 h
1	150	150	136	126	78	82	79	78
2	150	150	136	126	100	102	101	101
3	150	150	136	124	123	127	125	121
4	122	122	106	96	100	102	101	101
5	178	178	164	154	100	102	101	101

Specimen no.	Face width [mm]**				Penetration depth [mm]			
	9 h	6 h	3 h	12 h	9 h	6 h	3 h	12 h
🟥 1	9.8	10	9.7	9.3	🟥 3.2	🟥 2.4	🟥 2.3	🟥 2.6
🟥 2	9.9	9.7	9.1	8.7	🟥 3.2	🟥 1.9	🟥 2.2	🟥 2
🟥 3	9.7	9	8.7	8.1	🟥 2.9	🟥 1.8	🟥 2.1	🟥 1.7
🟥 4	8.2	8.1	7.9	7.1	🟥 2.4	🟥 2.4	🟥 1.9	🟥 1.8
🟥 5	11.3	10.9	🟥 10.4	11.2	🟥 3.4	🟥 3.2	3.5	🟥 3

Specimen no.	Weld face reinforcement (+) / incompletely filled groove (-)				Metal escape (+) / root concavity (-)			
	9 h	6 h	3 h	12 h	9 h	6 h	3 h	12 h
1	0	0,3	0	0	0	0	0	0
2	0	0,3	0	0	0	0	0	0
3	0	0	0,3	0	0	0	0	0
4	0	0	0	0	0	0	0	0
🟨 5	🟨 -0,3	0,8	0,6	0	0	0	0	0

* colour of a given space indicates a quality level: yellow – C; orange - D, red – unacceptable imperfection

** colour filling indicates an intermittent undercut of a weld face (5011/5012) or a burn-through (510) according to PN-EN ISO 6520-1

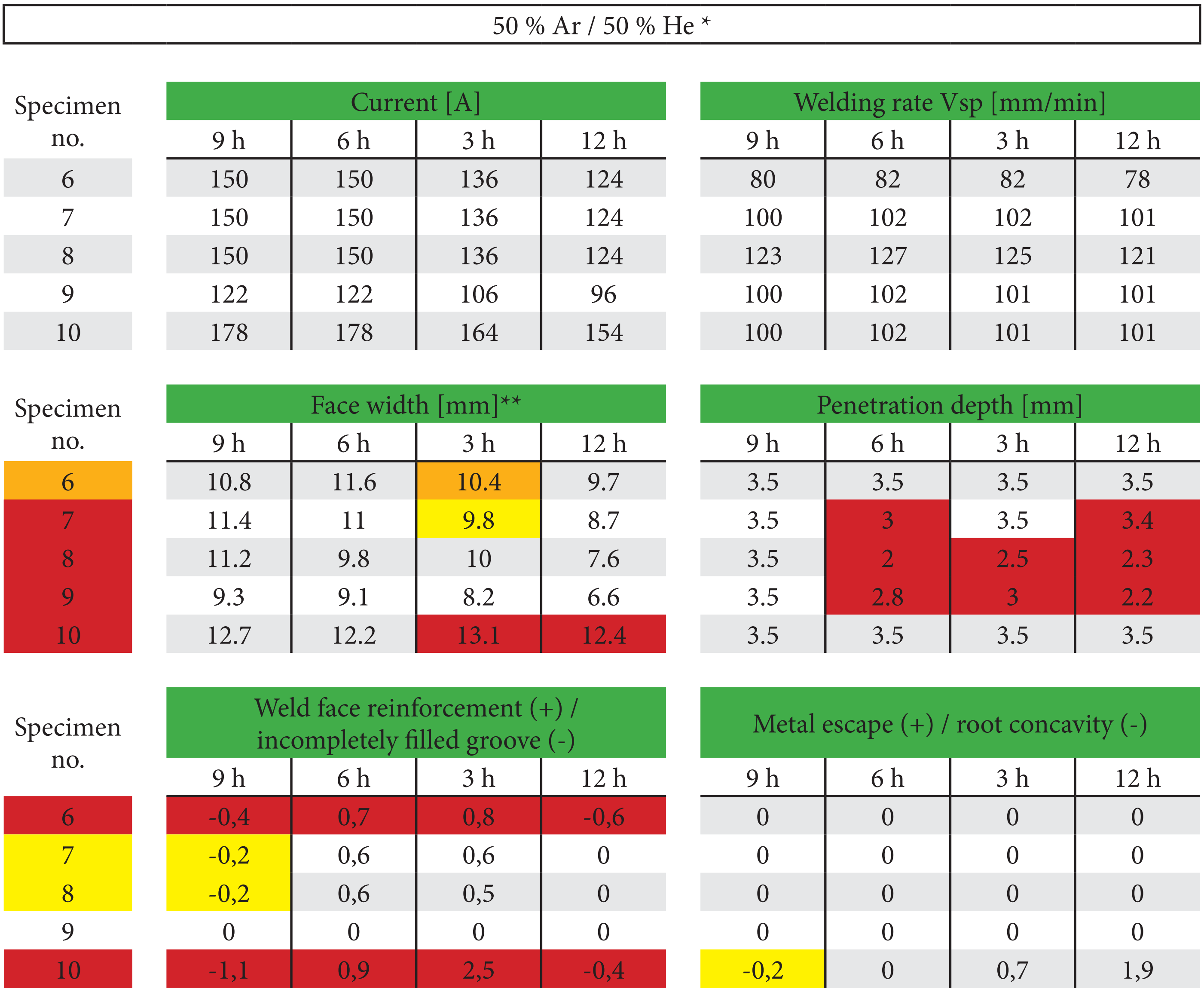
did not ensure full penetration on the entire circumference of a joint. At the same time, the area was free from welding imperfections, exceeding quality level B according to PN-EN ISO 5817 [2].

Figures 5 and 6 present diagrams showing the effect of a shielding gas used (Ar, Ar+He, He) on the dimensions of welds for individual quarters of a joint. The use of argon as an arc-shielding gas did not ensure the full penetration of a pipe having a wall thickness of 3.5 mm in any quarter of the joint (Fig. 6). The use of a shielding gas mixture containing 50% Ar and 50% He ensures the obtainment of full penetration only in the first quarter of the joint, with the face having the greatest width in this area. Helium ensures full penetration around the whole pipe circumference (Fig. 6) with the weld having the optimum width for the set of parameters used (Fig. 5).

Effect of Shielding Gas and Welding Parameters on the Quality of Welded Joints

Further tests involved investigating the effect of welding current quality and orbital welding rate on the shape of welds made in various positions. Welding shielded by technically pure argon makes it possible to obtain joints without

Table 2. TIG welding parameters, weld dimensions and the quality level according to PN-EN ISO 5817 of the test joints made with an Ar + He mixture used as a shielding gas



50 % Ar / 50 % He *

Specimen no.	Current [A]				Welding rate Vsp [mm/min]			
	9 h	6 h	3 h	12 h	9 h	6 h	3 h	12 h
6	150	150	136	124	80	82	82	78
7	150	150	136	124	100	102	102	101
8	150	150	136	124	123	127	125	121
9	122	122	106	96	100	102	101	101
10	178	178	164	154	100	102	101	101

Specimen no.	Face width [mm]**				Penetration depth [mm]			
	9 h	6 h	3 h	12 h	9 h	6 h	3 h	12 h
6	10.8	11.6	10.4	9.7	3.5	3.5	3.5	3.5
7	11.4	11	9.8	8.7	3.5	3	3.5	3.4
8	11.2	9.8	10	7.6	3.5	2	2.5	2.3
9	9.3	9.1	8.2	6.6	3.5	2.8	3	2.2
10	12.7	12.2	13.1	12.4	3.5	3.5	3.5	3.5

Specimen no.	Weld face reinforcement (+) / incompletely filled groove (-)				Metal escape (+) / root concavity (-)			
	9 h	6 h	3 h	12 h	9 h	6 h	3 h	12 h
6	-0,4	0,7	0,8	-0,6	0	0	0	0
7	-0,2	0,6	0,6	0	0	0	0	0
8	-0,2	0,6	0,5	0	0	0	0	0
9	0	0	0	0	0	0	0	0
10	-1,1	0,9	2,5	-0,4	-0,2	0	0,7	1,9

* colour of a given space indicates a quality level: yellow – C; orange - D, red – unacceptable imperfection

** colour filling indicates an intermittent undercut of a weld face (5011/5012) or a burn-through (510) according to PN-EN ISO 6520-1

visible shape imperfections. Imperfections, if any, are sporadic and only in one case did an undercut at 3 hours disqualified a joint. An incompletely filled groove at 9 hours was caused by an excessive heat input (the highest current at a welding rate of 100±2 mm/min) and, in the case of pipes having an overly small wall thickness, by difficulty related to a quick heat offtake. On the other hand, in none of the cases, except for the above-mentioned undercut at 3 hours, it was possible to obtain full penetration (Table 1) for the current intensity used (164 A). An attempted increase in welding current, aimed at the obtainment of full penetration of a pipe, proved unsuccessful as the weld pool was so large that at 12 hours an excessive metal outflow on the root side was observed and at 6 hours the liquid material stuck to the tungsten electrode, preventing further welding.

The shielding gas mixture containing 50% Ar and 50% He enabled the obtainment of full penetration in two extreme cases, i.e. at the minimum welding rate V_{sp} = 80±2 mm/min and welding current I = 150 / 150 / 136 / 124 A (specimen no. 6) and at the maximum current I = 178 / 178 / 164 / 154 A and a welding rate of V_{sp} = 100±2 mm/min (specimen no. 10). However, this entailed the presence of an incompletely filled groove in two successive quarters, which due to the fact that it is not a short welding imperfection, is classified as unacceptable. In addition, the specimens also contained intermittent undercuts of weld faces and root concavities. The joints without full penetration are characterised by imperfections of smaller sizes, i.e. a small incompletely filled groove or a minimum intermittent undercut of a weld face (specimen nos. 7 and 8).

Table 3. TIG welding parameters, weld dimensions and the quality level according to PN-EN ISO 5817 of the test joints made with He used as a shielding gas

Helium *

Specimen no.	Current [A]				Welding rate Vsp [mm/min]			
	9 h	6 h	3 h	12 h	9 h	6 h	3 h	12 h
13	150	150	134	124	80	82	80	78
14	122	122	106	96	100	102	100	98
15	150	150	136	126	123	128	125	122

Specimen no.	Face width [mm]**				Penetration depth [mm]			
	9 h	6 h	3 h	12 h	9 h	6 h	3 h	12 h
13	11.1	10.3	0	0	3.5	3.5	3.5	3.5
14	7	8.3	7.8	7.6	3.5	3.5	3.5	3.5
15	11.6	9.8	9.6	9.4	3.5	3.5	3.5	3.5

Specimen no.	Weld face reinforcement (+) / incompletely filled groove (-)				Metal escape (+) / root concavity (-)			
	9 h	6 h	3 h	12 h	9 h	6 h	3 h	12 h
13	-0.3	0.6	0	0	0	-0.2	0	0
14	-0.1	0.7	0.5	-0.3	0.3	0.1	0	1.2
15	-0.3	0.7	3.5	-1.7	0.5	0	1.5	1.1

* colour of a given space indicates a quality level: yellow – C; orange - D, red – unacceptable imperfection

** colour filling indicates an intermittent undercut of a weld face (5011/5012) or a burn-through (510) according to PN-EN ISO 6520-1

Helium, characterised by very high ionisation energy, enables the obtainment of full penetration already at current I = 122 / 122 / 106 / 96 A and a welding rate of V_{sp} = 100±2 mm/min. However, this results in the formation of welding imperfections – an incompletely filled groove in at least two quarters, which disqualifies the joint.

Also, for higher welding current values, the obtainment of full penetration was possible, yet connected with a greater number of welding imperfections. For I = 150 / 150 / 134 / 124 A and a welding rate of V_{sp} = 80±2 mm/min, a weld was burnt through at 3 hours; at 9 hours there was an incompletely filled groove, and root concavity was observed at 6 hours. The same current and welding rate higher by 50% led to the intermittent undercut of a weld face at 3 hours, an incompletely filled groove in two successive quarters i.e. at 12 and 9 hours and a significant excess weld metal at 3 hours.

Conclusions

1. Using the same orbital TIG welding parameters while welding AISI 304 (1.4301) austenitic stainless steel pipes having a wall thickness of 3.5 mm it was possible to obtain full penetration around the entire circumference only when helium was used as a shielding gas. The use of argon results in obtaining two times smaller penetration depth for a similar weld face width in individual positions.

2. Reducing a welding rate or increasing welding current during welding shielded with a mixture of argon and helium (50/50) enables the obtainment of full penetration around the entire circumference of pipe joints, yet, similarly as with helium used as a shielding gas, creates welding imperfections, mainly in the form of incompletely filled grooves at 9 and 12 hours and/or intermittent undercuts of weld faces at 3 hours, which in the case of both gases implies the necessity of using a filler metal in order to obtain properly-shaped joints.

3. The use of argon as an arc-shielding gas does not ensure the obtainment of full penetration in the adopted ranges of current and welding rate changes. A further increase in welding current results in a liquid metal escape, which in restricted positions, leads to short circuits and stops the welding process.

4. Orbitally TIG welded joints of austenitic steel pipes reveal the greatest concentration of welding imperfections at 3 and 9 hours (incompletely filled groove and intermittent undercuts of weld faces) irrespective of the shielding gas used.

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